Cyclical Dynamics of Airline Industry Earnings
Online Supplement

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OS1 Correction for the Endpoint Problem

The "endpoint" problem in model calibration arises when the data reported for a particular year does not match the time step against which it is compared. For instance, reported airline demand for 1977 is not available in the model until the first time step of 1978, because it is the sum of the demand for each time step during 1977. Therefore, when computing a stock such as the average ticket price over a particular year, the model reports the value at the beginning of the following year. To match this simulated data to the historical data, we call a table function that contains the historical data with the input (Time-1) for annual data and (Time – 0.25) for quarterly data.

OS2 Growth Adjusted Capacity Control

Airline travel demand exhibits long-term growth due to growth in population and income per capita. The growth trend and lag in acquiring capacity airlines mean airlines should plan for growth when acquiring capacity to ensure that capacity grows at the long-run expected growth rate without steady-state error. The model, and, more generally, models of industries with such growth trends, should allow for the possibility that the actors in the system are planning properly for the expected growth in demand. To do so, the decision rule for aircraft orders includes an adjustment for growth that ensures capacity shows zero steady state error under constant exponential growth.

To show that the formulation eliminates steady state error under exponential growth in demand, note first that in the steady state capacity, C, and the supply line of capacity on order, SL, must both grow at the same fractional rate, g, as demand:

$$\frac{dC}{dt} = g \cdot C \tag{A-1}$$

$$\frac{dSL}{dt} = g \cdot SL \tag{A-2}$$

Second, zero steady state error requires that capacity equal desired capacity, *C**, and that the supply line equal the desired supply line, *SL**:

$$C = C^* \tag{A-3}$$

$$SL = SL^* \tag{A-4}$$

Capacity will equal desired capacity in the steady state if the inflow of capacity acquisition equals the retirement of capacity, plus the increase in capacity needed to accommodate constant growth (assuming, reasonably, no net mothballing in steady state):

$$\text{Inflow}(C) = R + C \cdot g \tag{A-5}$$

The replacement orders, R, compensate for capacity retirements. By a similar argument, the supply line of capacity must equal the desired supply line and so the inflow to the supply line in the steady state must be:

$$\text{Inflow}(SL) = R + C \cdot g + SL \cdot g \tag{A-6}$$

Orders are the only inflow to the supply line, and are modeled as:

$$Orders = R + SLA + CA + GA \tag{A-7}$$

Where SLA is the supply line adjustment, CA is the capacity adjustment, and GA is the growth adjustment. Zero steady state error requires CA and SLA equal zero, since each adjustment is defined as the difference between the current and desired levels divided by the respective adjustment time. Equating the inflow to the supply line (A-6) with orders (A-7) gives:

$$R + GA = R + C \cdot g + SL \cdot g \tag{A-8}$$

and:

$$GA = C \cdot g + SL \cdot g \tag{A-9}$$

which are the corrections for growth used in the model. Note that the extent to which airlines, and other industries, actually account for anticipated growth when ordering capacity is an empirical question. We model this by including a weight, w, on the growth trend (eq. 4 and 5 in the paper). If the weight is one, there will be no steady state error in capacity under constant exponential growth. A weight of zero indicates no growth correction. In the full model the estimated weight on the growth trend is approximately 0.2 (Table 4), indicating that aggregate aircraft orders are not fully responsive to the growth trend.

OS3 Structural Sensitivity Tests

OS3.1 Modeling the Diffusion and Use of Yield Management

Yield management was introduced to the US airline industry in 1985, changing the response of aggregate prices to the demand/supply balance. We modeled the introduction of yield management to the industry in arguably the simplest way possible, with a step increase in its importance during the simulated year 1985. The simple structure performed very well during partial model testing. However, in reality, yield management was first introduced by American Airlines, and then adopted by other airlines. Further, yield management technology improved over time. Hence once might argue that the strength of the effect of the demand/supply balance on prices increased gradually over time after 1985. To test this possibility we ran the partial model test for price using a linear ramp for the effect of yield management on price in which the strength of the effect gradually rises from its pre-1985 value to a final value that is estimated, along with the time period over which the final value is reached.

The equation for the step response formulation is:

$$S_{SDP} = \mathrm{Base} + \mathrm{STEP(YM, 1985)} \quad \text{(A-8)}$$

Where S_{SDP} is the sensitivity of price to the demand/supply balance from Equation 15 in the paper, Base is the sensitivity prior to the introduction of yield management, YM is the effect of yield management on this sensitivity, and STEP is a step response function that takes the height of the step and the step time as its inputs. The equation for the ramp is:

$$S_{SDP} = \mathrm{Base} + \mathrm{RAMP[(YM - Base)/(T_F - 1985), 1985, T_F]} \quad \text{(A-9)}$$

RAMP in Equation A-9 is a function for a ramp that takes the slope of the ramp, the starting time, and the final time as inputs, T_F is the final time, and the slope calculation ensures that the total effect of yield management will be felt after the end of the ramp.

The estimation results (Table A1) show that using a ramp provides only marginal improvement in the model's fit and essentially no change in the estimated parameters. The time to adjust prices is the time constant from Equation 11 in the paper, the yield management effect is YM from the above Equations A-8 and A-9, the base effect is “Base” from Equations A-8 and A-9, target profit is “Target Profit per Passenger” from Equation 13, and the yield management ramp final time is T_F from Equation A-9. Given the low sensitivity of the results to the assumption of gradual introduction and adoption of yield management we retain the simple step formulation in the model analyzed in the paper.

Run	R^2	MAE/M	RMSE/M	U^m	U^s	U^c
Step Prices	86.4%	.0398	.0481	.0079	.0075	.9846
Ramp Prices	87.9%	.0392	.0464	0.0168	.022	.9610

Run/Variable	Time to Adjust Prices	YM Effect	Base Effect	Target Profit	YM Ramp Final Time
Step Prices	0.083	3.0	0	0.0332	N/A
Ramp Prices	0.083	3.9	0	0.0307	2000.7

Table A1: A comparison of the fit statistics and estimated parameters from partial model tests that use a step during 1985 and a ramp beginning in 1985 and ending in an estimated year to represent the introduction of yield management in the airline industry.

OS3.2 Capacity Constrained Aircraft Delivery

Manufacturing capacity constraints have likely been binding at various points in the post-deregulation history of the industry (the time horizon we consider). When industry manufacturing capacity is insufficient, aircraft delivery times will lengthen, possibly affecting the stability and other properties of the cycle in the airline industry. Further, airlines may respond to longer delivery times by ordering farther ahead or perhaps even placing speculative orders, potentially affecting stability and other properties of the industry cycle, as seen in other industries (e.g., Sterman 2000, Ch. 18). To include these dynamics in the model we attempted to gather time series from Boeing and Airbus for orders, cancellations, and deliveries but were unable to find these data from publicly available sources over a long enough time horizon to calibrate the model. Most of the data cover individual airframes, individual airlines, or a small number of years, whereas aggregate data for US airlines from 1977 through 2010 are needed to estimate the potential impact of capacity constraints or forward-ordering.

Absent data enabling us to estimate either manufacturing capacity or delivery times we chose to represent aircraft ordering with the standard stock control formulation, adjusted for growth, and assuming a constant average delivery delay for new aircraft. Of course the effective average time constant for expanding the fleet in service in our model is variable, as it depends not only on the manufacturing time constant but also on the stock of mothballed aircraft, which is explicitly modeled. When there are no mothballed aircraft, the manufacturing time determines the rate at which the fleet can be expanded. When there are mothballed aircraft, the effective fleet expansion time is shorter, as aircraft can be returned to service from mothballing faster than new aircraft can be built.

Nevertheless, it remains possible that during times of high demand manufacturing capacity will limit deliveries, increasing the average aircraft delivery delay and potentially encouraging airlines to “order further ahead” or “over-order”. To test whether capacity limits and ordering ahead significantly change the stability of airline profits we conducted a structural sensitivity test that incorporated endogenous aircraft manufacturing capacity.

Figure A2 shows the structure added for this sensitivity test. The structure accomplishes three things. First, it limits the flow of aircraft out of the supply line to be, at a maximum, manufacturing capacity. Second, manufacturing capacity is assumed to respond with a lag to the required capacity, determined by the required delivery rate and normal manufacturing capacity utilization. Third, it captures ordering-ahead by increasing the desired supply line (and as a result, the orders) of the airline industry when the actual delivery delay of aircraft increases.

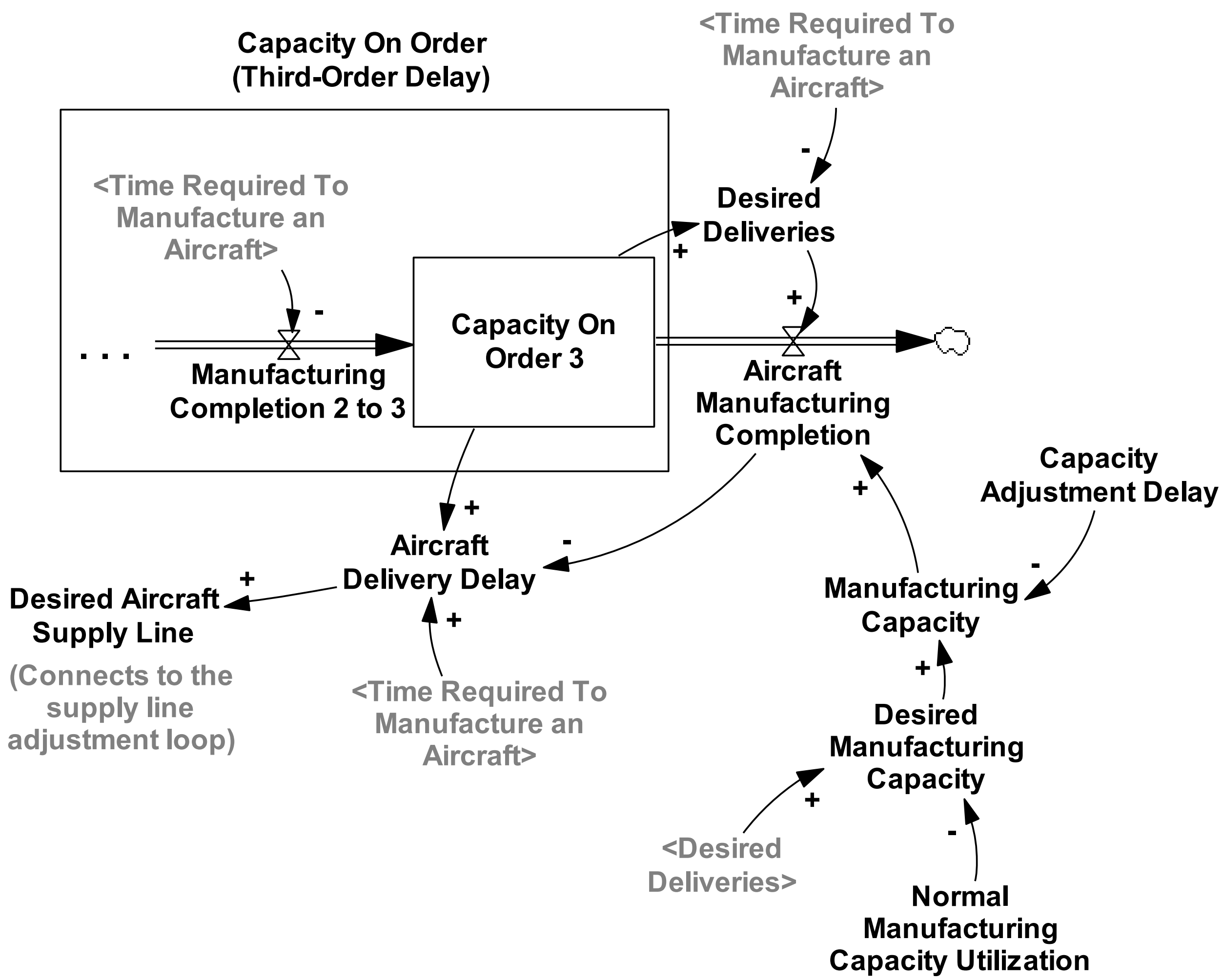


Figure A2: The added structure that causes manufacturing capacity to act as a constraint on deliveries of aircraft.

The equations for these changes are:

1. Desired Aircraft Supply Line = Desired Capacity Acquisition Rate*(2/3*Time Required to Manufacture an Airplane + Aircraft Delivery Delay)

   We chose to modify only the third stock in the supply line for simplicity, and because capacity constraints will have their biggest impact on planes currently under construction, not ones that are waiting in the queue as orders or materials.

2. Aircraft Delivery Delay = Capacity on Order 3/Aircraft Manufacturing Completion

   This change combines with the one above to help capture the ordering ahead dynamic. When the actual completion flow is small relative to the supply line on order the delivery delay rises and airlines order more than they otherwise would.

3. Aircraft Manufacturing Completion = MIN(Desired Deliveries, Manufacturing Capacity)

When there is not enough capacity planes are only completed at the maximum possible rate.

4. Manufacturing capacity = SMOOTH3(Desired Manufacturing Capacity, Capacity Adjustment Delay)

Capacity adjusts with a delay to the desired level.

5. Desired Manufacturing Capacity = Desired Deliveries/Normal Manufacturing Capacity Utilization

The goal for manufacturing capacity is the level of capacity that will complete planes at the desired rate, adjusted by normal manufacturing capacity utilization.

6. Desired Deliveries = Capacity on Order 3/Normal Delivery Time

Manufacturers seek to meet the normal delivery time.

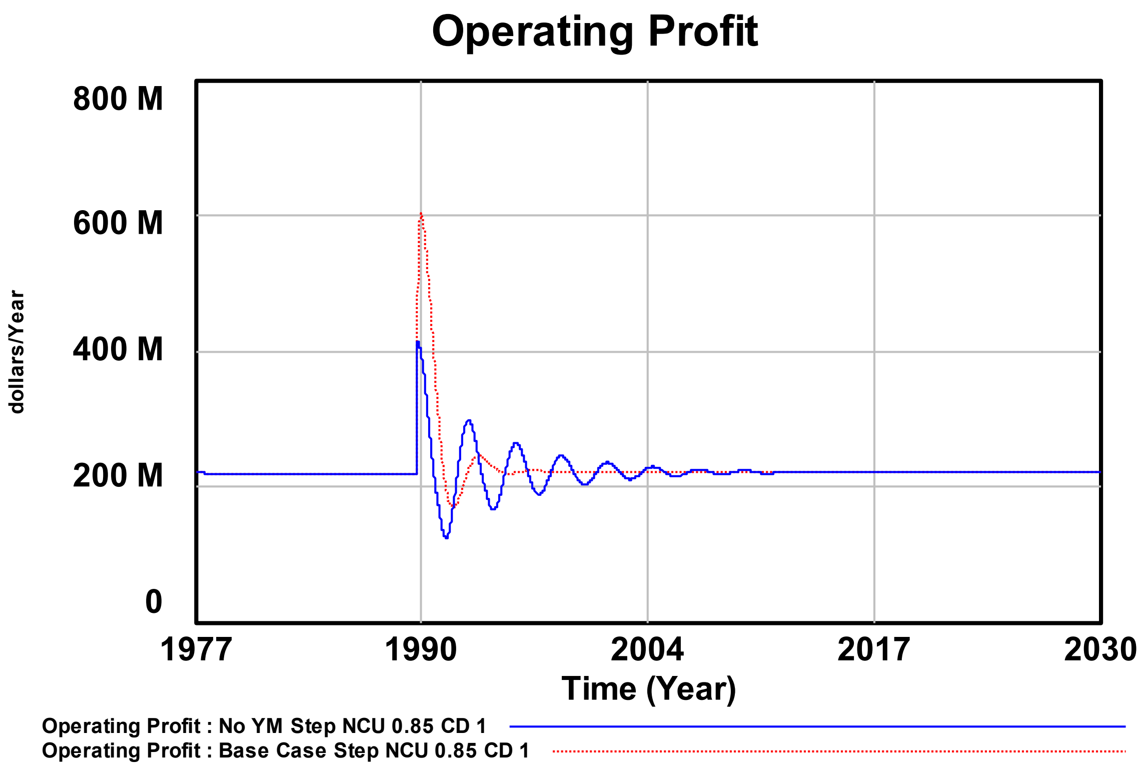
7. Normal Delivery Time= Time Required to Manufacture an Airplane/3

We divide by three because the supply line is a third order delay and the capacity constraint only applies to the last stock in the material delay.

The file "Airline Ordering Structure Sensitivity.mdl" includes the structure for endogenous manufacturing capacity and aircraft delivery times.

The impact of manufacturing capacity on the stability of both airline profits and capacity is determined by two constants: normal manufacturing capacity utilization (NCU) and the capacity adjustment delay (CD). Since we cannot estimate values for these parameters without additional data we instead preformed a series of tests over the range of plausible parameter values. The lower limit for normal capacity utilization was set to 85% because a 1% step in demand results in almost no change to the delivery delay using this value. The upper limit for capacity utilization is 100%. We varied the capacity adjustment delay between 1 year in the low case and 5 years in the high case.

In all four cases, spanning the plausible region of the parameter space for normal capacity utilization and the capacity adjustment delay, the impact of yield management on the stability of profit is qualitatively the same as in the uncapacitated model. The removal of yield management always decreases the stability of the profit cycle and reduces operational leverage. Increasing in the strength of yield management always increases the stability of the cycle and operational leverage.



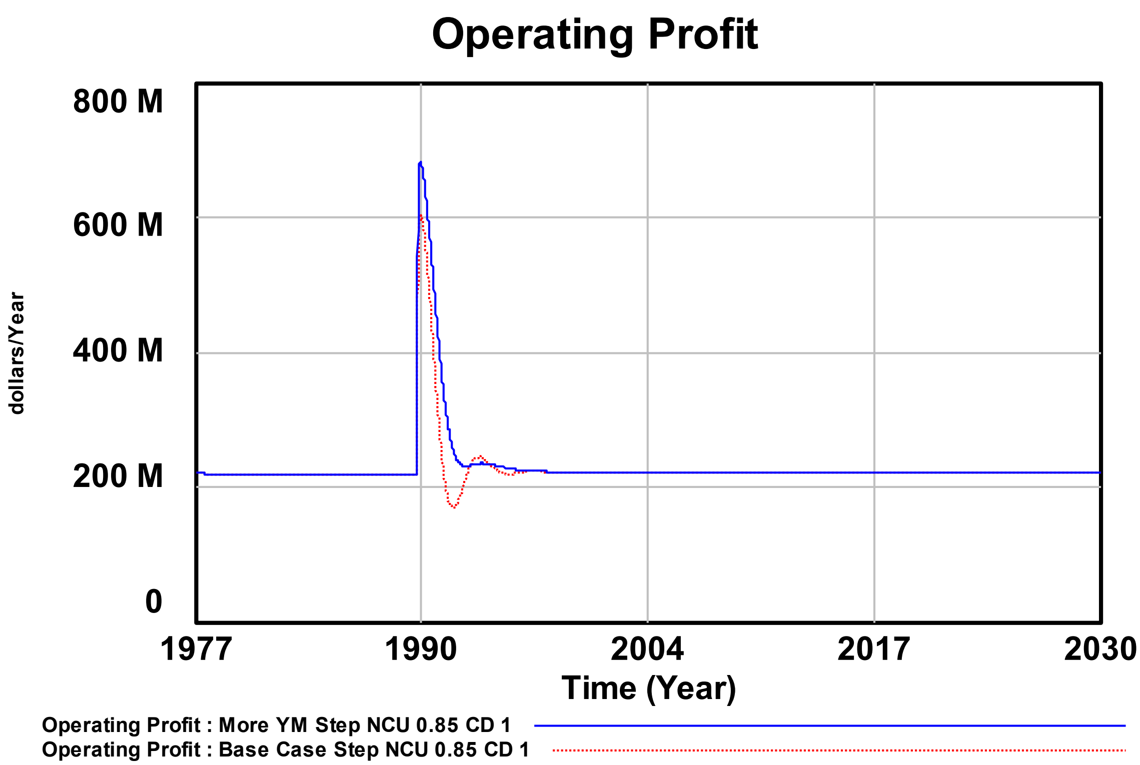
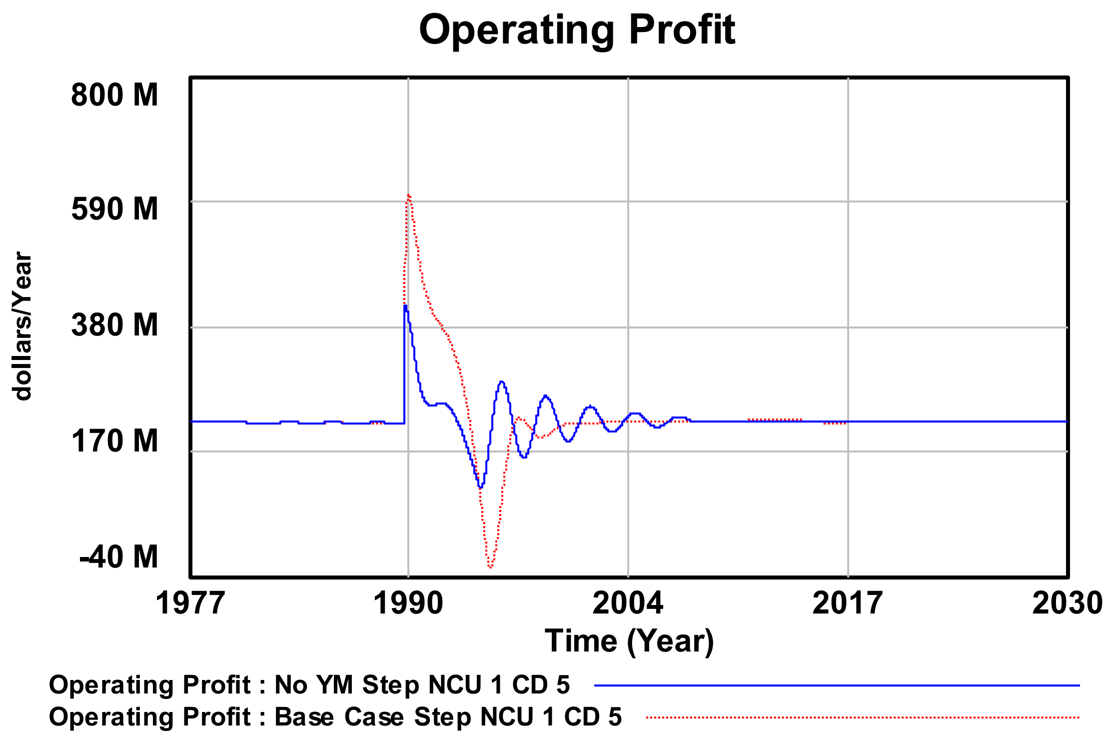


Figure A3: Step tests of the sensitivity of our results to capacity constrained aircraft manufacturing. This case used the low values for both normal manufacturing capacity utilization (NCU) and the capacity adjustment delay (CD).



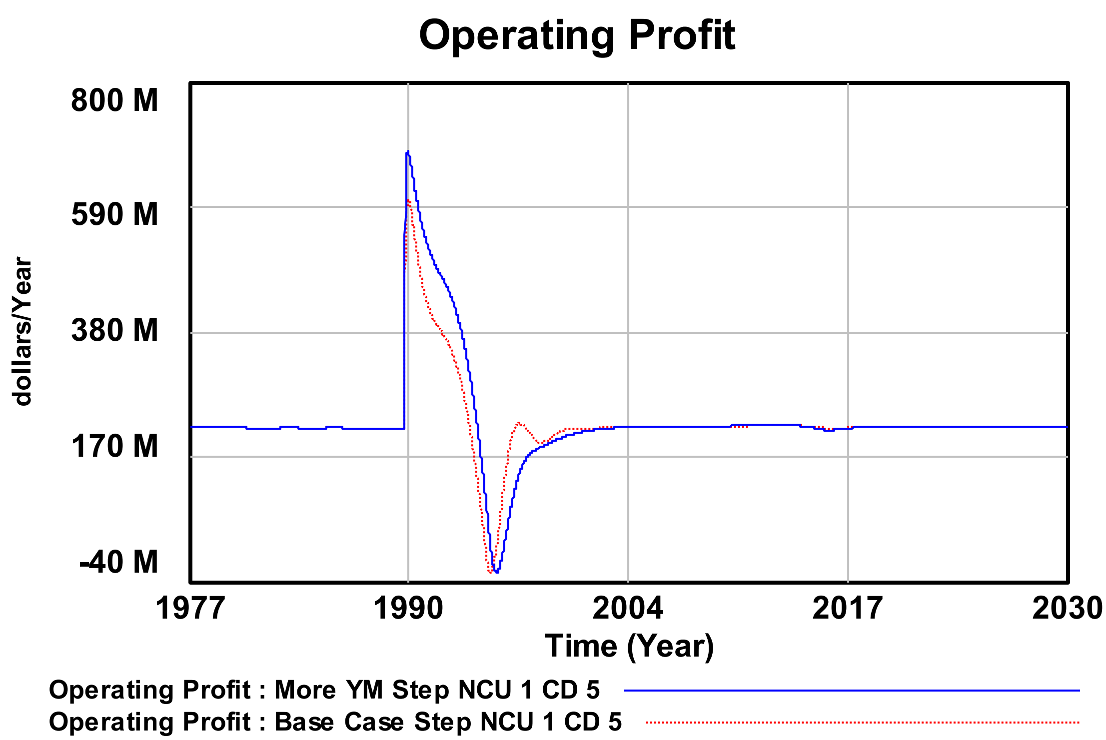
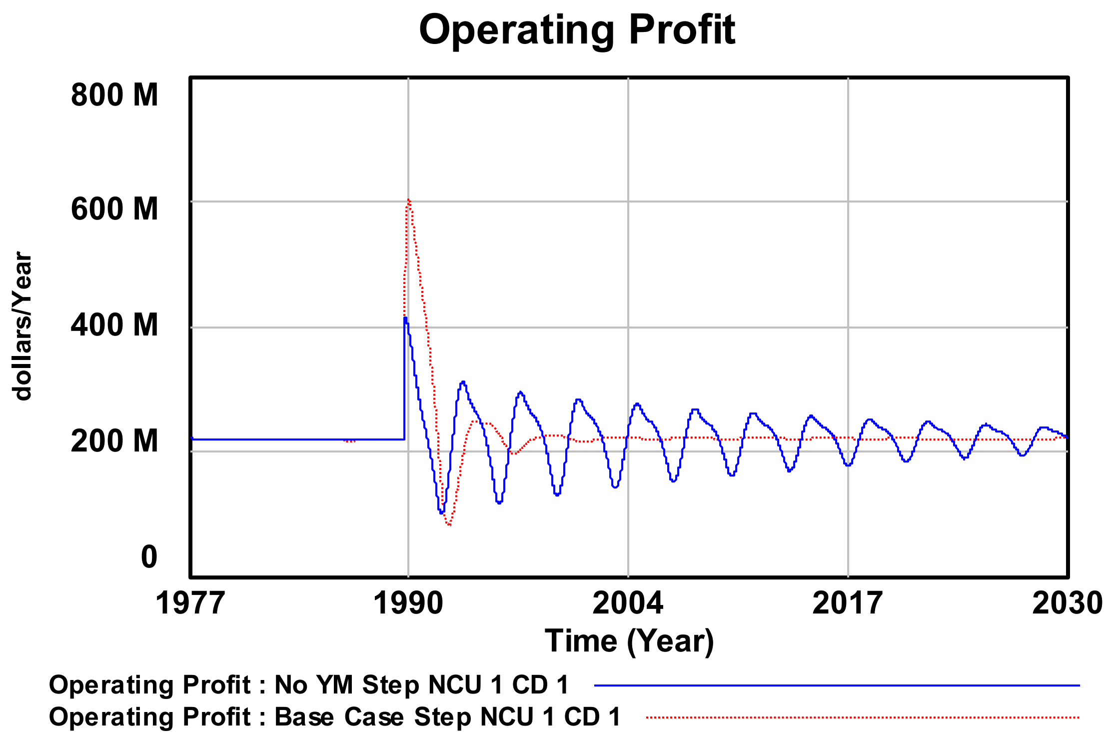


Figure A4: Step tests of the sensitivity of our results to capacity constrained aircraft manufacturing. This case used the high values for both normal manufacturing capacity utilization (NCU) and the capacity adjustment delay (CD).



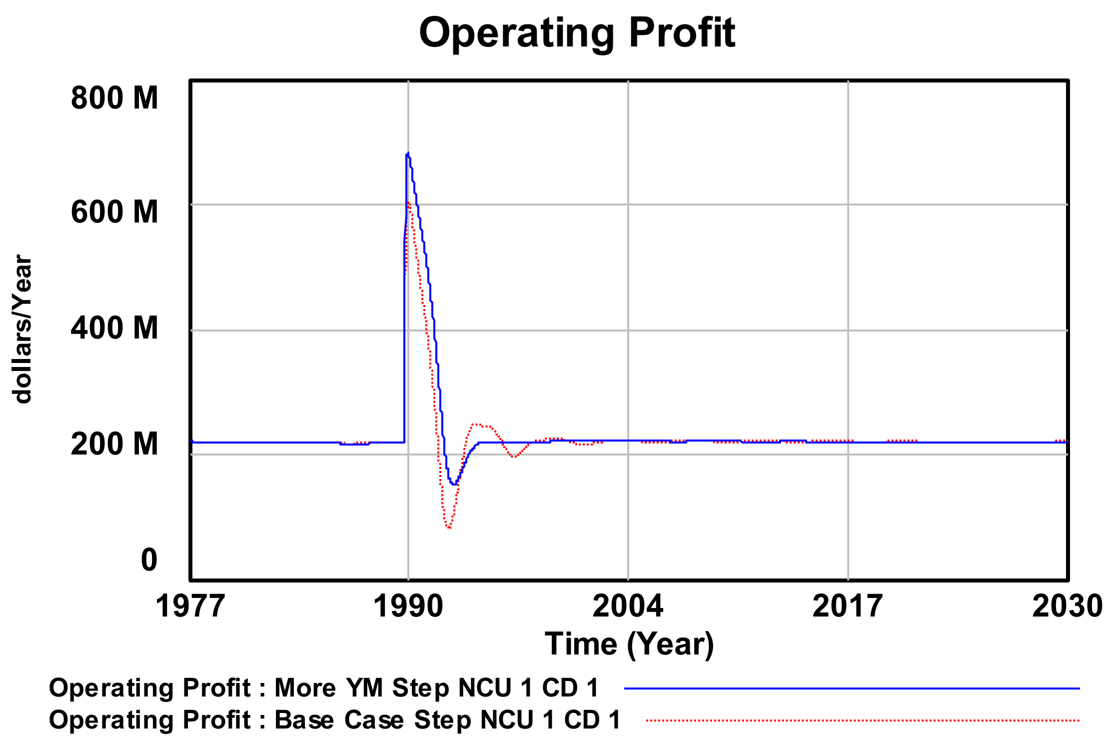


Figure A5: Step tests of the sensitivity of our results to capacity constrained aircraft manufacturing. This case used the high value for normal manufacturing capacity utilization (NCU) and the low value for the capacity adjustment delay (CD).

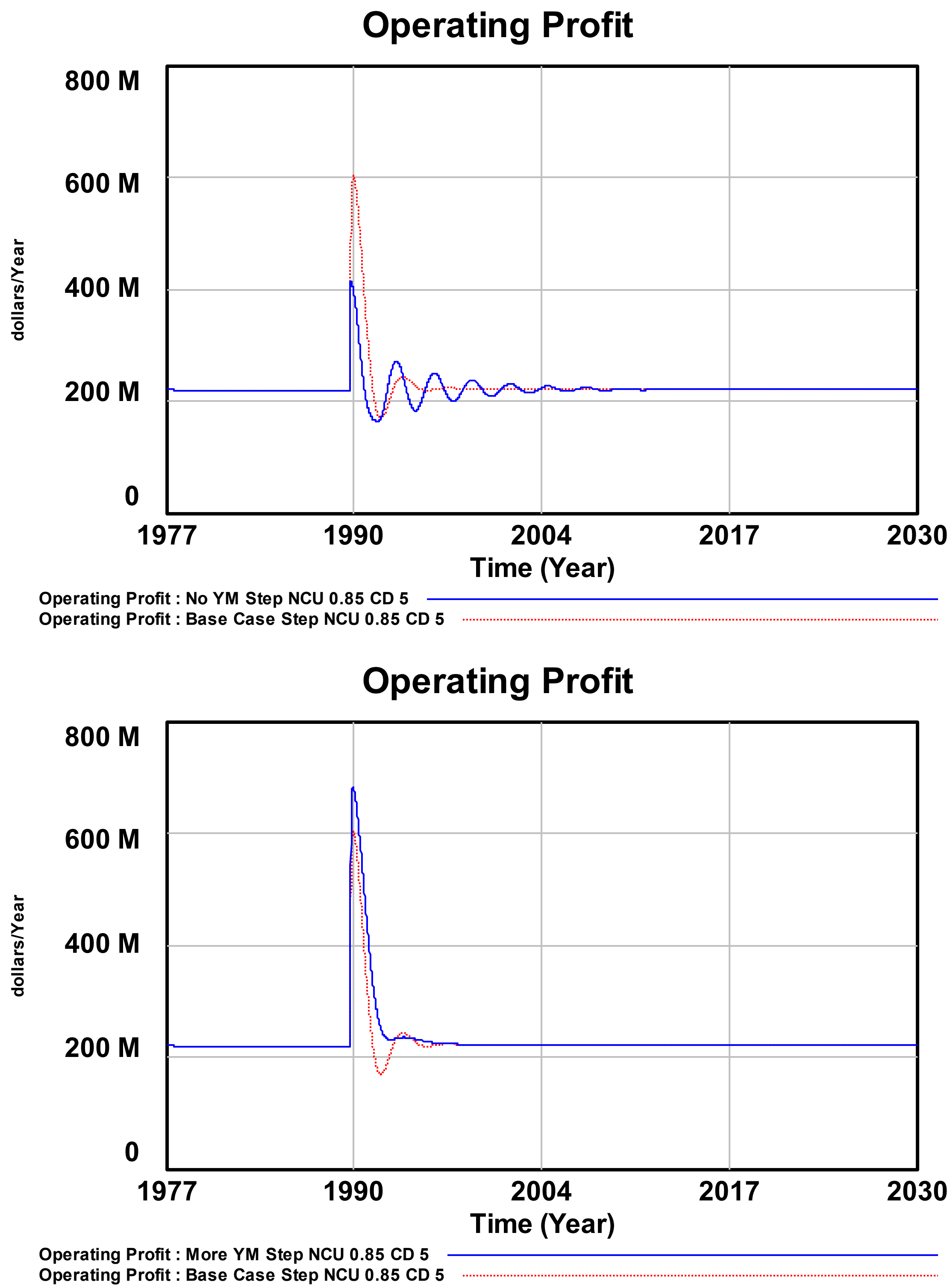


Figure A6: Step tests of the sensitivity of our results to capacity constrained aircraft manufacturing. This case used the low value for normal manufacturing capacity utilization (NCU) and the high value for the capacity adjustment delay (CD).

The inclusion of aircraft manufacturing capacity constraints would, of course, alter the best-fit parameters, but the results show it does not change the impact of yield management on the nature and stability of the profit cycle.

While adding structure to constrain capacity would make the model more realistic, it would also make it less verifiable. Absent data enabling the structure for endogenous capacity to be estimated it would not be prudent to include that structure, particularly since assuming a constant delivery delay does not change our conclusions about the impact of yield management.

OS3.3 The Sequential Removal of Feedback Loops and its Impact on Operating Profit

The following is a series of tests using the full model structure that sequentially remove different feedbacks, so as to gain insight into which feedbacks contribute to the origin and stability of the industry cycle. Figure A7 shows the base case of the model.

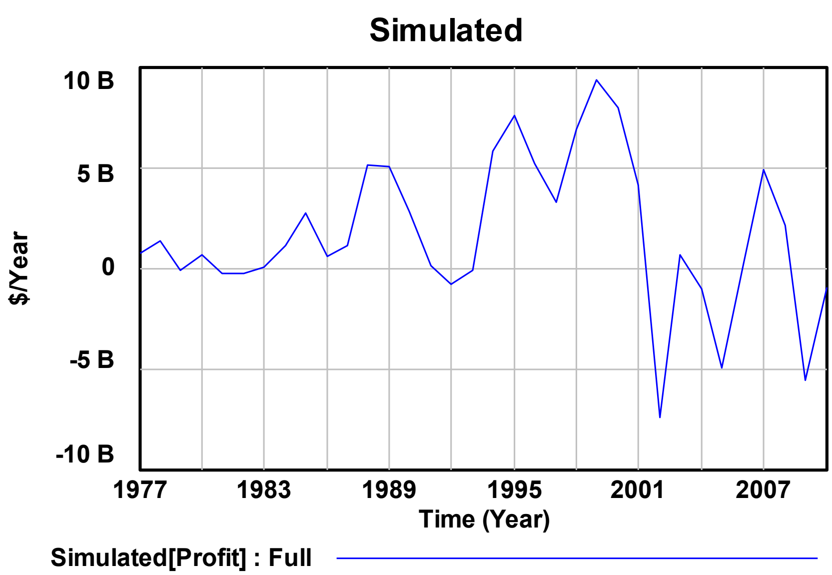


Figure A7: Simulated operating profit in the base case of the full model.

Figure A8 shows simulated operating profit after eliminating the supply line adjustment feedback (setting the "weight on supply line adjustment" variable to 0 on the "Load Factor and Capacity" view). The modeled cycle in profits is relatively unchanged from the base case, but the shorter period cycle is reduced.

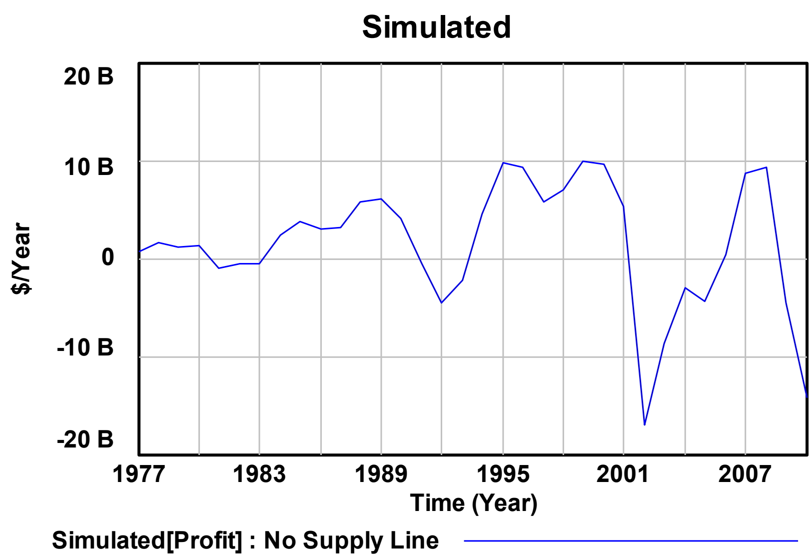


Figure A8: Simulated operating profit when the supply line adjustment feedback is eliminated from the full model.

Figure A9 shows simulated operating profit after the elimination of both the supply line feedback and the yield management feedback (setting the "Effect of Yield Management on the Sensitivity of Price to Demand Supply Balance" to 0). The amplitude of the profit cycle is substantially reduced after yield management is removed, but the cycle is not eliminated (note the change in vertical scale).

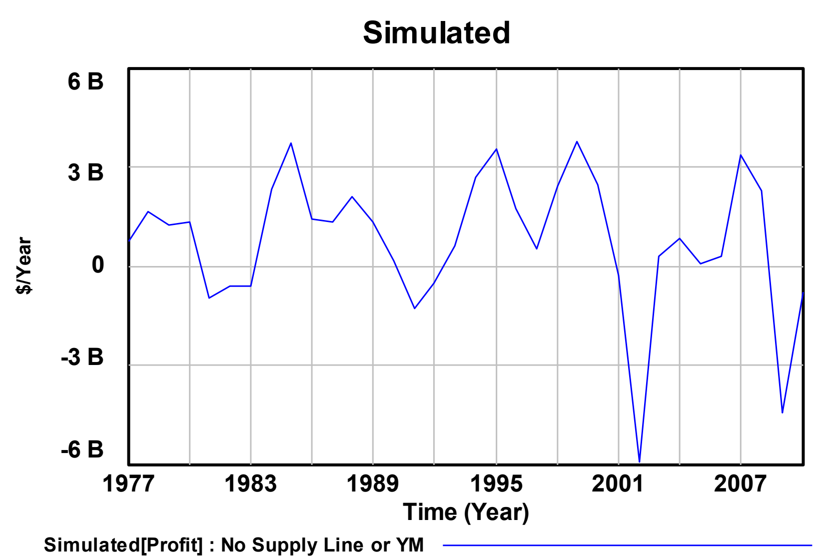


Figure A9: Simulated operating profit when the supply line adjustment feedback and yield management are eliminated from the full model.

Figure A10 shows simulated operating profit after the elimination of the supply line feedback and the strengthening of the yield management feedback (setting the "Effect of Yield Management on the Sensitivity of Price to Demand Supply Balance" to 7.56, compared to the base case value of 3.78). The amplitude of the profit cycles is substantially increased when aggregate prices respond more forcefully to load factors (again, note the change in vertical scale).

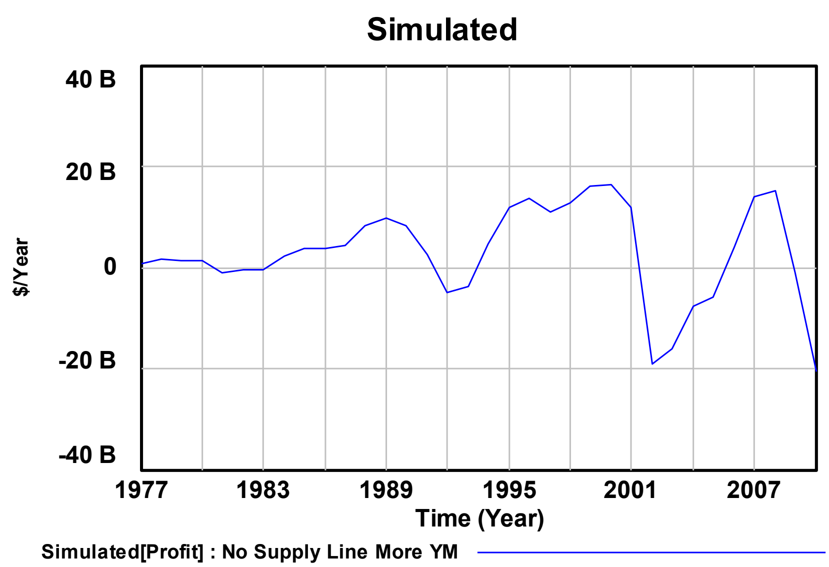


Figure A10: Simulated operating profit when the supply line adjustment feedback is eliminated from the full model and the strength of the yield management feedback is doubled.

Few other feedbacks in the model strongly affect the profit cycle when excluded. Removing the unemployment effect on demand, the 9/11 shock, and the price elasticity of demand (setting the "Strength of Unemployment Effect on Demand", "Size of 9/11 Effect", and "Price Elasticity of Demand" to zero) further reduces profit volatility compared to test 2, as shown in Figure A11.

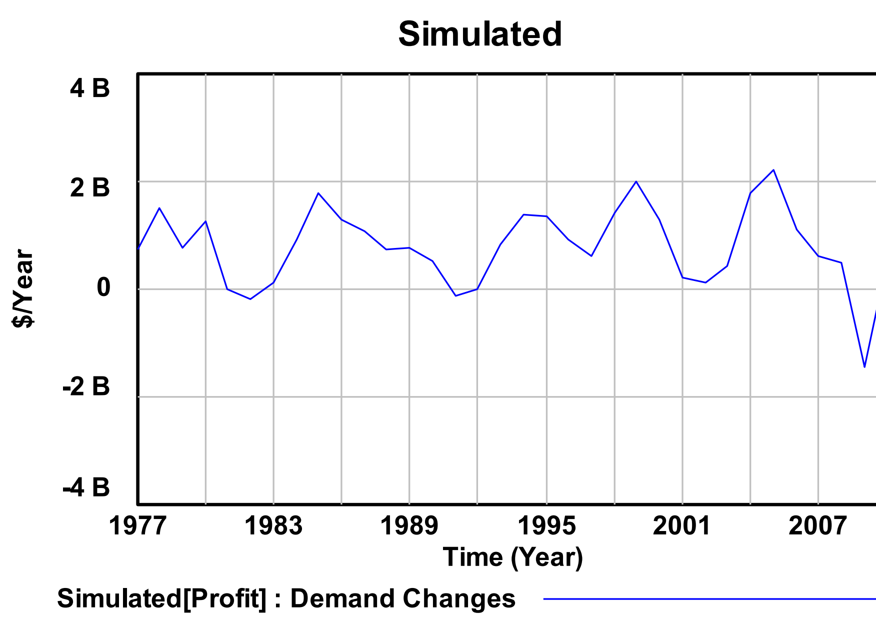


Figure A11: Simulated operating profit when the supply line adjustment feedback, yield management, the effect of unemployment on demand, the September 11th shock, and price elasticity are eliminated from the full model.

OS4 Additional Files

Part of this online supplement is a collection of files that include several important resources for those interested in replicating and extending our results. These files help to fulfill the minimum and preferred documentation guidelines for system dynamics models (Rahmandad and Sterman, 2012). In particular we provide:

- Vensim readable .mdl files of the full model and all of the sensitivity tests we performed.
- Full model documentation created using the SDM-Doc tool (Martinez-Moyano, 2012).
- The .vpd and .voc files that we used for the full model optimization procedures described in the paper (partial model tests are subsets of these files).
- Excel workbooks that provide details on the load factor regression and the calculation of the stability metrics.

References

Martinez-Moyano I. 2012. Documentation for model transparency. *System Dynamics Review*, **28**(2): 199-208

Rahmandad H, and Sterman J. 2012. Reporting guidelines for simulation based-research in social sciences. *System Dynamics Review*, **28**(4): 396-411.

Sterman J. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. McGraw-Hill: Boston.